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14. ABSTRACT

The acquired computing cluster is used in the development of novel techniques for computational fluid dynamics and continuum mechanics, with focus on large Eulerian or Lagrangian discretizations. Applications that receive particular emphasis include:
- Simulation of discontinuous flows resulting from the interaction of several immiscible or chemically reacting phases
- Adaptive discretizations of large fluid volumes that can however resolve turbulent flows and the effect of highly variable bottom topography
- Coupling of Lagrangian deformable or rigid objects to Eulerian discretizations of fluid volumes
- Simulation of nonlinear and anisotropic elastic continua under extreme deformation, severe impact and fracture scenarios.
Significant progress in these areas is reflected in the research publications (list attached) which became possible largely due to the availability of the granted equipment.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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List of Publications
ONR Grant N00014-05-1-0479

Losasso, F., Shinar, T. Selle, A. and Fedkiw, R., "Multiple Interacting Liquids", SIGGRAPH 2006, ACM TOG 25 (2006).

Irving, G., Guendelman, E., Losasso, F. and Fedkiw, R., "Efficient Simulation of Large Bodies of Water by Coupling Two and Three Dimensional Techniques", SIGGRAPH 2006, ACM TOG 25 (2006).

Hong, J.M., Shinar, T., Kang, M. and Fedkiw, R., "On Boundary Condition Capturing for Multiphase Interfaces", J. Sci. Comput., (in review).

Sifakis, E., Selle, A., Robinson-Mosher, A. and Fedkiw, R. "Simulating Speech with a Physics-Based Facial Muscle Model", ACM SIGGRAPH/Eurographics Symposium on Computer Animation (SCA), edited by M.-P. Cani and J. O.Brien, 2006.

A Computing Cluster for Numerical Simulation

[ONR N00014-05-1-0479]

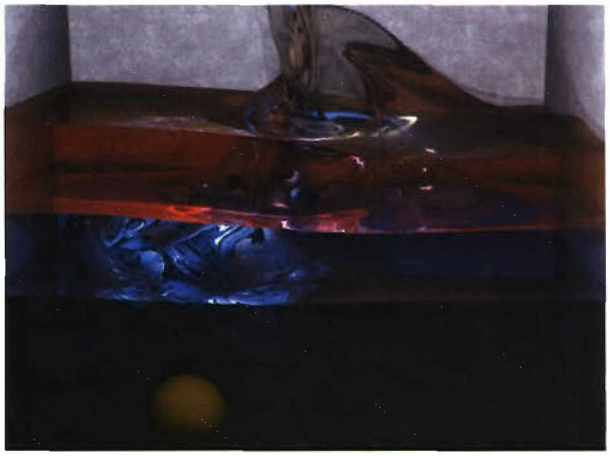
PI: Ronald Fedkiw

Final Project Report

This report provides a summary of the applications and algorithms whose development was enabled by the acquisition of the equipment allowed by the grant. We also outline the impact of this parallel computing resource on our future research roadmap.

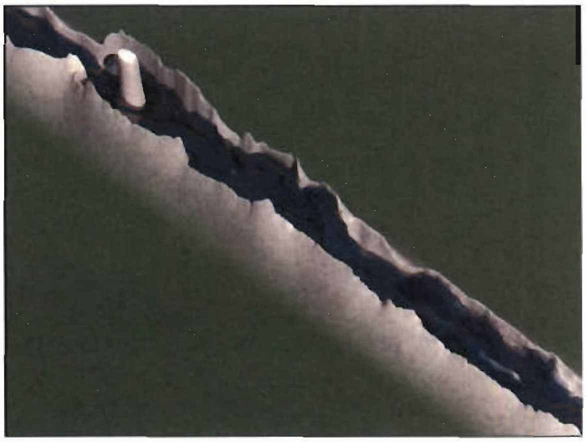
Computational Fluid Dynamics

One of the most important advances enabled by the availability of our parallel cluster resource was the development of parallel codes for Computational Fluid Dynamics simulation. This allowed for the resolution of phenomena such as the interaction of multiple immiscible or chemically reacting fluid phases. In [LSSF] we built on the particle level set method [EFFM] while extending it to the simulation of multiple fluids on the same simulation grid. Approaches such as the Ghost Fluid Method have been successfully employed to resolve the difficulties of integrating the Navier-Stokes equations in the presence of discontinuities in the state variables occurring across region boundaries corresponding to distinct phases, such as water and air or liquid fuel and gaseous combustion products. However, additional complications occur when more than two phases interact in ways that may give rise to triple points, where preventing the formation of vacuum or material overlap is particularly challenging. The work of [LSSF] (see also [HSKF]) proposes a method for applying jump conditions across discontinuities without the explicit need for ghost cell storage, computing them on the fly instead. Additionally it proposes a novel projection method that eliminates the problems of vacuum formation or material overlap while preserving the signed distance property for the levelset functions providing the representation of the fluid volume. Such advances were particularly important in improving the efficiency of partitioning and communication schemes required for the mapping of CFD computations across a grid of processors, while reducing the parallelization overhead. In conjunction with the use of grid-conscious preconditioning schemes this allowed for the simulation of complex scenarios such as the interplay of fluid phases of varying viscosity, density and viscoelastic behavior at uniform resolutions never before feasible on individual CPUs after mapping to several parallel nodes (typically as many as 24-32).



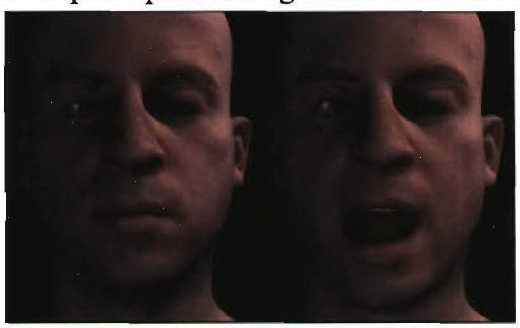
Beyond the mapping of general uniform grid discretizations to a parallel array of computing nodes, we investigated discretization methods that are explicitly optimized for

simulation on parallel hardware. Adaptive discretizations such as octree structures [LGF] map well to single CPU platforms or shared memory systems. Clustered hardware presents a preference for uniform grids which minimize and simplify the geometry of partition boundaries, across which information needs to be propagated. In [IGLF] we proposed a hybrid approach that combines the uniform structure of a 2D Cartesian grid with the compactness of representation offered by a Run Length Encoding scheme. We hybridize the two discretizations by using the the uniform grid along the horizontal dimensions and compress the vertical dimension using the RLE scheme. A number of uniform cells are maintained around the air-water interface to resolve the detail of flow near the surface. We use this hybrid grid to discretize the full Navier-Stokes equations instead of resorting to a deep water or shallow water approximation to reduce our problem to two dimensions. Mapping to a horizontal grid of processors is straightforward since the partition boundaries are planar surfaces. We have successfully simulated grids at a resolution as high as 2000x200 for the horizontal component of the grid, after mapping to a linear array of 16 processors.



Continuum mechanics

We have successfully applied Finite Element formulations to create anatomically and biomechanically accurate simulations of the human musculoskeletal system [TSBNLF] as well as facial expessions [SSRF]. Both cases exemplify the importance of efficient and scalable simulation frameworks for deformable continua, since they both demand use of simulation meshes in excess of one million tetrahedral elements. In [SSRF] we exploited the time independence property of quasistatic simulation to partition a facial expression analysis and simulation task in time, before dispatching it to more than 40 computing nodes for parallel batch processing, to obtain a full muscle-based description of the phonemic spectrum of a subject. Such analyses may be used in speech synthesis, prediction of impacts of surgical corrections to facial motion and speech articulation and virtual surgery planning. We are currently working on a fully parallel Finite Element simulation framework using a spatial, rather than temporal partitioning which will enable the parallelization of time-dependent integration schemes such as the semi-implicit Newmark used in [BFA,ITF,TSBNLF]. Mapping complex continuum mechanics simulations to clustered hardware will enable resolutions of several million elements, needed for full-body active musculature simulation and enable applications such as facial reconstructive surgery planning to



operate at near-interactive rates, dramatically increasing their impact and usability in medical environments. Finally, we seek to extend methods for dynamically changing solid topology [MBF,BHTF] to operate in a parallel simulation environment to enable large-scale simulations of material damage resulting from impact or model the process of tissue cutting and suturing during a simulated virtual surgery.

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FINAL EQUIPMENT LIST

ONR GRANT NUMBER N-00014-05-1-0479
STANFORD SPONSORED PROJECTS NUMBER 32336
A COMPUTING CLUSTER FOR NUMERIC SIMULATION

Type of Equipment	Manufacturer and Model Number	Quantity	Cost
Compute Servers	Sun Fire V40z compute nodes Sun Fire V20z compute nodes	20	$391,853
Rack/Cabinets	Sun Rack 1000-38	10	4,195
Cables and switches	Nortel Baystack Switches	18	4,220
Backup system for 20-node cluster	Sun StorEdge 3511 Rack Ready	1	13,170
Additional compute node	Sun Fire X4100	1	8,995
TOTAL COST			**$422,433**